UCRL-JC-126188
PREPRINT

A User Facility for Research on Fusion Systems with Dense Plasmas

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This paper was prepared for submittal to
2nd Symposium on Current Trends in International Fusion Research:
Review and Assessment
Washington, DC
March 10-14, 1997

January 7, 1999

Lawrence Livermore National Laboratory

A USER FACILITY FOR RESEARCH ON FUSION SYSTEMS WITH DENSE PLASMAS

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1. Introduction

There are a number of fusion systems whose dimensions can be scaled down to a few centimeters, if the plasma density and confining magnetic field are raised to sufficiently high values. These systems include the field-reversed configuration (FRC), spheromak, Z-pinch, multiple mirrors, and some others. The fusion-grade plasma in these systems can be obtained with the energy deposited to the plasma as low as 10-100 kJ. This prompts a "user-facility" approach to the studies of this class of fusion systems. The concept of such a user facility was first briefly mentioned in Ref. 1. Here we present a more detailed description.

The user facility would consist of a pulsed energy source (presumably a Marx generator) and a set of diagnostics permanently deployed at the facility site. Research groups could bring their own "targets" (experimental assemblies of a few centimeters size, see below for some specific examples) to perform a series of experiments at the facility. Because of their small size, the "targets" would be relatively inexpensive, and thus well within the reach of the university groups. The concept and design of the targets would be entirely the mission of the participating groups. The availability of such a user facility for performing experiments should have a strong favorable effect on the creative potential of fusion research.

The main energy source could be a Marx generator with the stored energy up to 1 MJ and the pulse-length in the microsecond range. Certain pulse-shaping capacity would increase the range of possible experiments. A couple of separate energy sources with the energy content up to 100 kJ, for generating the bias magnetic field, would be desirable. The interface of the Marx generator and the load can be made very flexible.

The set of diagnostics should include optical, UV, and x-ray spectroscopy; neutron diagnostics (for both DD and DT neutrons, with tritium used as a trace element); optical imaging; and x-ray backlighting. The typical time-scale of plasma processes for the aforementioned fusion systems will not be shorter than 30-50 ns. Particular research groups might also provide their own diagnostics.

There is a similarity between the concept of a user facility presented in this paper and the concept of international center for the studies of plasma focus presented by Herrera [2]. Perhaps, a combination of the two would rise the chances for the actual creation of such a facility. There already exist examples of large facilities which serve, at least in part, as user facilities. The Nova laser in the Lawrence Livermore National Laboratory is used by a numerous university groups; the Z facility at Sandia National Laboratories (fast Z pinch) is a site of a number of collaborative multi-institutional experiments. The proposed facility would allow research groups with limited resources to contribute in a significant way to development of several fusion concepts.

2. Examples of possible experiments

To be more specific, we consider in more detail two possible experiments related to the FRC. The first is the study of the formation and properties of an FRC with the density n~10^{18} cm^{-3}, the temperature T~100 eV, and the magnetic field strength B~100 kG. This set of parameters corresponds to

$$\beta \equiv \frac{16\pi nT}{B^2} \sim 1. \tag{1}$$

The radius of the FRC can be a~1 cm, and the length L~4-6 cm. Such an object could then be adiabatically compressed by an imploding liner (see Ref. 3 for a more detailed discussion and further references).

Magnetic coils of a radius $\sim 1.5a$ would be used for creating the bias magnetic field and for the field reversal. The bias coil can have a relatively long pulse, up to a hundred microseconds. There should not be any problems in creating such a coil. The field-reversal coil should be turned on within a time of order of several axial Alfven transit times [4],

$$\tau = \alpha L / \mathrm{v}_A, \tag{2}$$

with α being of the order of 2. For the aforementioned set of parameters, and for a deuterium plasma, one has τ~ 1 μs. This estimate sets the time-scale for the controlled changes of the magnetic field.

The total energy content in the plasma will be ~ 1 kJ, and the magnetic energy will be several times higher, ~ 3 kJ (because the magnetic field occupies a larger volume). For τ~ 1 μs, the power level involved into the process of field reversal will be ~3 GW. The current in the coil,

$$I \sim \frac{cBL}{4\pi}, \tag{3}$$

should be $\sim 1.5 \cdot 10^{15}$ CGS~0.5 MA (for B~100 kG and L=6 cm). The required loop voltage will be of the order of 7.5 kV. All these parameters are not very demanding and can be reached even without use of the main energy source. In this experiment, the pulsed magnetic system can possibly be designed so as to survive multiple shots.

At the temperature of 100 eV, the plasma will be fully ionized, and its radiative losses will be [5]:

$$P_{rad}(W) = 1.7 \cdot 10^{-32} n^2(cm^{-3}) T^{1/2}(eV) \cdot \pi a^2(cm) L(cm) \tag{4}$$

For the parameters given above, this power will be only 2.5 MW, much less than the total power delivered to the plasma during the reconnection event, 1 kJ/1 μs ~ 1 GW. This means that radiative losses from a pure plasma are negligibly small. For radiative losses to become considerable, the plasma should become very dirty, with the amount of heavy impurities (of the type of iron) in the range of 1%.

The FRC with the aforementioned parameters will have a ratio of plasma radius to a characteristic ion gyro-radius of ~30-50, much higher than in the existing experiments and very close to the values of this parameter expected for a FRC-based fusion reactor [4].

If successful, this experiment will pave the road to the second one, where the pre-formed FRC will be translated into an imploding liner of the type described in Ref. 3 and then adiabatically compressed. We conceive of a scenario where the on-axis hole through which the FRC will be injected will be closed early in the implosion, thereby trapping the FRC inside the liner. This can be achieved by using a liner whose linear density (mass per unit length) on the injection end is smaller than over the rest of its length (Cf. Ref. 6)

The compression should be 3-dimensional, because in 3D implosions the energy is delivered predominantly to the plasma, not to the embedded magnetic field (Cf. Ref. 3). The feasibility of quasi-spherical implosions has been demonstrated in the experiments by Degnan et al (Ref. 7). In geometrically self-similar 3D implosions, the plasma temperature scales as

$$T = T_0 C^2 \tag{4}$$

where C is a linear convergence (the ratio of the initial dimension to the instantaneous dimension). If one starts with the plasma wit the temperature T_0=100 eV, the fusion-grade plasma needs reaching C~7-10. Note that, in the aforementioned experiments by Degnan et al, the maximum linear convergence was close to 7. According to the analysis carried out in Ref. 3, the life-time of the hot dense state is determined by the liner expansion under the action of the plasma pressure. For the liners with a mass of a few grams, one can obtain the fusion gain Q ~ 1. The energy delivered to the liner should be in the range of 100-200 kJ. Assuming that the efficiency of the energy transfer from the condenser bank to the liner is ~10%, one sees that the energy stored in the condenser bank should be 1-2 MJ. This sets the scale for the main energy source for the user facility.

The experimental assembly will now have to be replaced after every shot (for this reason, we have used the word "target" to designate the experimental assembly). But since the target is compact (with the maximum dimension not exceeding 10-15 cm), manufacturing a few dozen targets for one experimental campaign should be inexpensive. We imply that the experimental group will bring these targets to the user facility and "shoot" them out within a couple of weeks.

3. Diagnostics issues.

The possibility of providing a set of sophisticated diagnostics permanently deployed at the user facility is one of the most attractive features of the user facility approach (the diagnostics constitute, possibly, the most expensive part of the hardware). For the configurations where the plasma is not obscured by the liner, one can use spectroscopy to measure relative line intensity, Stark broadening, Doppler broadening, possibly with a deliberate adding of trace impurities. The electron density and temperature could be measured by Thomson scattering. Faraday rotation could be used for the measurements of the magnetic field. Optical and UV imaging could be used to view an overall structure of the plasma configuration. For the configurations obscured by the liner, one could perform X-ray imaging (provided the liner material is transparent in the chosen band) and neutron diagnostics. X-ray backlighting could be used to observe the interface between the plasma and the liner. In some cases (in particular, if one implodes a mirror-like configuration), the presence of the liner would still allow using axial viewing ports.

4. Development of stand-off energy sources

An important part of the activities centered around the user facility, could be development of stand-off energy sources for pulsed fusion devices based on liner implosions. A problem with such devices is that, in every implosion, a large amount of energy is released from the fusion plasma. If implosion occurs at the tips of the electrodes of the power supply system, an unacceptable thermo-mechanical damage to an expensive hardware occurs. Certainly, a commercial fusion reactor cannot operate in such a mode.

A possible way of solving this problem was delineated in Ref. 3, where it was suggested that the fusion reactor would work in the following way: the experimental assemblies will be dropped into explosion chamber (whose walls would be protected by liquid lithium, very much as in ICF reactors, Ref. [8]), and the energy required to drive the implosion will be delivered from the distance of tens of meters (see below).

It is assumed that the assembly in this case will contain the following elements: i) the system for pre-forming the FRC (or other configuration to be adiabatically compressed); ii) the liner; iii) the on-board circuitry required to energize various systems in a required sequence (formation of pre-plasma, translation it into the liner, liner implosion).

There are at least two ways of delivering the energy to the assembly dropped into the explosion chamber. The one is to use the "inverse diode" system [3], where the assembly would be energized by an 1-MeV electron beam, penetrating through the entrance foil, being absorbed by a cathode, and generating a voltage between the foil and the cathode. With an appropriate circuitry (including, possibly, a pulse transformer) installed in the assembly, this energy source could be used to drive some fast circuits. The second way is based on the use of fast flyers accelerated either electromagnetically (Ref. 9) or explosively (Ref. 10). These flyers could then be used to compress the conducting flux conserver enclosing some seed magnetic field (which could be generated, in particular, by the inverse diode system). The kinetic energy of the flyer would be converted into the magnetic energy and the latter would drive a circuit of the imploding liner. The flyers with velocities of order of 10^7 cm/s were obtained in electromagnetic accelerators, with the flyer energy ~ 100 kJ [9]. Explosively driven cumulative jets with velocities up to $9 \cdot 10^6$ cm/s were obtained [10].

The studies of detached energy sources are at present in their infancy, and the contribution of the groups working at the user facility could be very important. All the diagnostics deployed for the studies of plasma physics issues, can be used effectively also for the studies of operation of the prototypical energy conversion systems (inverse diode, magneto-explosive generators, etc).

5. Discussion

The 3D liner implosions can also be used to adiabatically compress some other closed-field-line configurations, like the spheromak and even a spherical tokamak (with a central post mounted inside the liner). Although an imploded spherical tokamak may not have a great future as a fusion reactor, it may allow reaching a new parameter domain in terms of plasma beta and thereby add substantial new information to the physics of tokamaks.

Purely radial liner implosion on a multimirror system with a dense plasma would provide favorable experimental conditions for the studies of the wall confinement (see Ref. 11) – an issue of great importance for many pulsed systems with dense plasmas, including MAGO [12]. The advantage of the open-ended system is the presence of an axial access.

All in all, creation of a user facility for studies of pulsed systems with a dense plasma would add a new dimension to fusion research. It would give opportunity to numerous university research groups to fully develop and demonstrate their creative potential. It would also be an excellent way to build up an international collaboration on innovative fusion concepts.

Acknowledgment

This work was performed under the auspices of the U.S. Department of energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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